

Prospects for Probing Triple Gauge-boson Couplings at the LHC

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Abstract.

In these proceedings I explore one aspect of gauge-boson physics at the LHC—Triple Gauge-boson Couplings (TGCs) in WZ and $W\gamma$ production. Methods for extracting confidence limits on anomalous TGCs are assessed, while accounting for the effects of higher order QCD corrections and contributions from other theoretical and detector related systematics. Detector response has been parametrised according to the ATLAS detector's specifications. A strategy for reporting the anomalous coupling limits is introduced which removes the ambiguities of form factors by reporting the limits as a function of a cutoff operating on the diboson system invariant mass. Techniques for measuring the energy dependence of anomalous couplings are demonstrated.

INTRODUCTION

The HCP 2004 talk associated with these proceedings covered the more general topic of gauge-boson physics at the LHC. I reviewed prospects for the measurement of the W -mass [1, 2], the electroweak mixing angle from the forward-backward asymmetry in dilepton production [3], Triple Gauge-boson Couplings in diboson production, and the production of three gauge bosons [4]. I highlighted some of the many challenges associated with making such measurements, including the simulation of processes for which accurate Monte Carlo predictions are missing (see Ref. [5] for a review of relevant event generator techniques) and the need for supporting measurements of parton density functions and luminosity.

I have chosen to focus these proceedings on the topic of Triple Gauge-boson Couplings in $W\gamma$ and WZ production, since most of the other topics appear in published form elsewhere, and recent TGC results have not yet appeared in the public domain. More detailed descriptions of these TGC studies can be found in ATLAS Internal Notes [6, 7] and Ref. [8]. These processes have been studied in the context of the CMS detector in Ref. [9, 10, 11, 12].

Triple Gauge-boson Couplings

In the Standard Model (SM), the gauge-bosons interact not only with matter particles, but also with one another. These interactions manifest themselves as couplings between three (or more) gauge-bosons, such as a WWZ or $WW\gamma$ coupling, referred to

as triple gauge-boson couplings (TGC's). The existence of these couplings has been beautifully verified at LEP [13, 14, 15, 16]. TGCs are tightly connected with the symmetry properties of the SM and reflect the full mathematical gauge group structure of the fundamental interactions. This gauge structure produces cancellations in the production of W^+W^- and WZ pairs. Without these cancellations, the cross section for longitudinally polarised W^+W^- and WZ pairs would grow proportional to the diboson invariant mass squared, violating unitarity at relatively low energies. Because these cancellations are so important for the consistency of the model, it is necessary to test them at the highest accuracy possible. The production of gauge-boson pairs in hadronic collisions provides a direct test of these couplings. While the $pp \rightarrow W^+W^-$ mechanism receives contributions from both the WWZ and $WW\gamma$ coupling, the $pp \rightarrow WZ$ and $pp \rightarrow W\gamma$ channels allow for the direct independent measurement of the WWZ and $WW\gamma$ couplings respectively. Other gauge-boson self interactions such as ZZZ , $ZZ\gamma$, $Z\gamma\gamma$, and $\gamma\gamma\gamma$ vertices are not allowed in the Standard Model, because neither the Z nor the γ carries charge or weak isospin which are the quantum numbers to which the gauge-bosons couple (anomalous TGCs in $pp \rightarrow ZZ$ and $pp \rightarrow Z\gamma$ have been studied in the context of the LHC in Refs. [10, 17, 18, 19]). Vertices containing an odd number of W -bosons (WZZ , $W\gamma\gamma$, $WZ\gamma$, WWW) are excluded by charge conservation. The self interactions also encompass interactions between four gauge-boson (quartic couplings).

The most general Lorentz and gauge invariant anomalous WWZ vertex which conserves charge and parity is described by an effective Lagrangian with 3 *model independent* anomalous TGC parameters Δg_Z^1 , $\Delta \kappa_Z$, and λ_Z . The corresponding $WW\gamma$ vertex is described by 2 parameters $\Delta \kappa_\gamma$, and λ_γ . These parameters are all zero in the SM, and strictly speaking may be energy dependent (see discussion below). Experimental attempts to measure anomalous TGC parameters probe the low energy remnants of new physics which may be operating at a much higher energy scale. Measurements of this type would be most interesting in the scenario where direct searches for new particles which affect the gauge-boson interactions fail to observe any substantial deviation from the SM.

The study described in this paper is optimised for “low luminosity” ($10^{33} \text{cm}^{-2} \text{s}^{-1}$) LHC conditions. It focuses on the $pp \rightarrow W\gamma \rightarrow l^\pm \nu \gamma$ and $pp \rightarrow WZ \rightarrow l^\pm \nu l^+ l^-$ processes (where l^\pm is an electron or muon). Detector effects have been included in the form of a fast parametrisation [20] of the ATLAS detector response. Next-to-leading order (NLO) QCD corrections to diboson production are large at LHC energies, particularly in the physically interesting region of high transverse momentum which is the region of maximum sensitivity to anomalous TGC's. These effects have been accounted for using the NLO Baur, Han, and Ohnemus (BHO) generators [21, 22]. The BHO generators have been modified to provide event weights as a function of the anomalous coupling parameters, as discussed in the appendix of Ref.[7]. For events with a coloured parton in the final state, PYTHIA 6.136 [23] is used for independent fragmentation and subsequent hadronization of the coloured parton.¹ PYTHIA 6.136 has been used for the

¹ The standard parton shower approach cannot be applied to the events produced by the BHO generator, because this would double count regions of phase space. See Ref. [5] for a description of recent advances in this subject.

simulation of the background processes, with a single constant k -factor of 1.5 applied to roughly account for the effect NLO corrections might have on the total background rate. Background rates and shapes have a relatively small impact on the confidence limits reported in this paper. As such, background simulations using next-to-leading order matrix elements are not expected to change the results significantly.

BACKGROUNDS AND EVENT SELECTION

The $WW\gamma$ and WWZ vertices will be probed at LHC using the muon and electron decay channels, $pp \rightarrow W\gamma \rightarrow l^\pm \nu \gamma$ and $pp \rightarrow WZ \rightarrow l^\pm \nu l^+ l^-$. These processes provide striking detector signatures consisting of high transverse momentum charged leptons and/or a photon, together with missing transverse momentum. Events can be triggered either with the single muon, single electron, and/or the high P_T photon triggers. Hadronic decay channels are difficult to separate from QCD backgrounds, and the addition of these channels are not expected to significantly improve the precision of the measurements.

The kinematic selection criteria for this analysis have been optimised not only to maximise the signal significance, but also to minimise the effect of systematics and to maximise the sensitivity to anomalous TGCs. For the purpose of optimising these cuts, a leading order signal simulation with showering and hadronization is used. This avoids the possibility that the event selection makes use of the differences in the simulation methods that have been used for signals and backgrounds (e.g. a cut on the number of jets would take advantage of the fact that the NLO signal simulation can produce only one final state hard jet).

Several backgrounds will mimic the $W\gamma$ signal. The most important background processes are:

$W(\rightarrow \tau \nu)\gamma$ with leptonic tau decays This process is also sensitive to the TGC vertex, but is considered a background for the purposes of this study since the τ 's are more difficult to reconstruct. The contribution from this process will be reduced by lepton transverse momentum cuts, because the secondary charged leptons from the τ -decay will have reduced transverse momentum as compared to the direct lepton from the W -decay. At Tevatron energy, this effect renders the leptonic τ decay background negligible [24]. This is not the case at LHC energy.

$Z^0\gamma$ production with leptonic decays, with one charged lepton escaping detection.

Heavy flavours $t\bar{t}(\gamma)$ and $b\bar{b}(\gamma)$ Though the signature for these events is very different from the signal, the cross section is so high that the tails of these distributions become important. The primary defence against these events is a simple jet veto. It may be possible to further improve the selection by rejecting those events in which a top quark can be reconstructed.

Z^0 +jet and W +jet production, with the jet mis-identified as a photon. This is the most challenging background. Its contribution will depend strongly on the particle ID capabilities of the detector.

The selection criteria for the $W\gamma$ analysis are: (1) one isolated photon with $P_\gamma^T > 100$ GeV, $|\eta_\gamma| < 2.5$ and no other reconstructed photon with $P_\gamma^T > 80$ GeV, $|\eta_\gamma| < 2.5$, (2) one isolated electron or muon, $P_{l^\pm}^T > 25$ GeV, $|\eta_{l^\pm}| < 2.5$ and no other charged lepton

TABLE 1. The number of events surviving after each of the kinematic cuts for the $W\gamma$ analysis is applied cumulatively for an integrated luminosity $\mathcal{L} = 30 \text{ fb}^{-1}$. The γ -jet, $b\bar{b}(\gamma)$, and $W \rightarrow l\nu\gamma$ processes have been included in the background totals, but are not shown individually in the table.

	$Z\gamma$	W +jet	Z +jet	$t\bar{t}(\gamma)$	$W\gamma \rightarrow \tau\nu\gamma$	all Backgrd	$W\gamma$ Signal
$P_{\gamma}^T > 100 \text{ GeV}$	1277	2097	2101	945	665	8153	10638
$P_{l^{\pm}}^T > 25 \text{ GeV}$	1196	1938	1800	837	586	7098	10066
$P_{\text{miss}}^T > 25 \text{ GeV}$	377	1557	215	689	574	3511	7311
$\Delta R(\gamma, l^{\pm}) > 1$	376	1543	183	611	574	3385	6791
$\sum_{\text{jets}} \vec{P}_{\text{jet}_i}^T < 100 \text{ GeV}$	341	1280	133	286	534	2623	4262

TABLE 2. The number of events surviving after each of the kinematic cuts is applied cumulatively for the WZ analysis for an integrated luminosity $\mathcal{L} = 30 \text{ fb}^{-1}$.

	Z +jet	ZZ	$t\bar{t}$	All Backgrd	WZ Signal
3 leptons, $P_{l^{\pm}}^T > 25 \text{ GeV}$	398	500	461	1359	3285
$P_{\text{miss}}^T > 25 \text{ GeV}$	3.2	90	357	450	2453
$ M(l^+, l^-) - M_Z < 10 \text{ GeV}$	2.8	76	65	144	2331
$\sum_{\text{jets}} \vec{P}_{\text{jet}_i}^T < 100 \text{ GeV}$	2.5	72	44	119	1987

with $P_{l^{\pm}}^T > 20 \text{ GeV}$, $|\eta_{l^{\pm}}| < 2.5$, (3) missing transverse momentum $P_{\text{miss}}^T > 25 \text{ GeV}$, (4) vector sum of jet transverse momenta (jet veto) $\sum_{\text{jets}} \vec{P}_{\text{jet}_i}^T < 100 \text{ GeV}$, (5) charged lepton to photon separation $\Delta R(l^{\pm}, \gamma) = \sqrt{\Delta\phi^2 + \Delta\eta^2} > 1$, and (6) a solution for the neutrino longitudinal momentum exists which is consistent with it arising from a W . The effect of these cuts on the signal and background rates are tabulated in Table 1. About 6900 event candidates will be observed with an integrated luminosity of 30 fb^{-1} , 2600 of which will be background.

There are very few backgrounds which are able to mimic the leptonic WZ signal. The most important backgrounds are (1) ZZ production with leptonic decays and one lepton escaping detection, and (2) $t\bar{t}$ production with both of the W 's from the top quarks decaying leptonically and a b -jet producing a third charged lepton. The contributions from each background process are shown in Table 2.

The selection criteria for the WZ analysis are: (1) three isolated electron or muons, $P_{l^{\pm}}^T > 25 \text{ GeV}$, $|\eta_{l^{\pm}}| < 2.5$ two of which are like flavour, opposite sign leptons satisfying $|M(l^+, l^-) - M_Z| < 10 \text{ GeV}$, (2) no other charged lepton with $P_{l^{\pm}}^T > 20 \text{ GeV}$, $|\eta_{l^{\pm}}| < 2.5$, (3) missing transverse momentum $P_{\text{miss}}^T > 25 \text{ GeV}$, (4) vector sum of jet transverse momenta (jet veto) $\sum_{\text{jets}} \vec{P}_{\text{jet}_i}^T < 100 \text{ GeV}$, (5) a solution for the neutrino longitudinal momentum exists which is consistent with it arising from a W . About 2100 event candidates will be observed with an integrated luminosity of 30 fb^{-1} , 119 of which will be background.

NLO corrections degrade the TGC sensitivity because a large number of extra diagrams are included in the calculation, the majority of which do not include the TGC vertex. The NLO corrections become largest when the jet activity is significant. This means that a cut on the vector sum of the jet transverse momenta $\sum_{\text{jets}} \vec{P}_{\text{jet}_i}^T$ will serve to moderate the influence of these extra diagrams. When $\sum_{\text{jets}} \vec{P}_{\text{jet}_i}^T$ is small, the signal is Born-like. When it is large, the diboson system will be recoiling against a hard central jet, and the influence of the TGC vertex will be minimal.

The $\sum_{\text{jets}} \vec{P}_{\text{jet}_i}^T$ cut is optimised strictly on the basis of the sensitivity to the anomalous TGC's. As the cut is increased, the signal purity goes down, but at the same time the sensitivity increases until a maximum is reached at about 100 GeV. This is because the signal itself (in kinematic regions where the anomalous TGC's have little effect) is washing out the sensitivity.

ANOMALOUS COUPLING CONFIDENCE LIMITS

The expected statistical confidence intervals for anomalous TGCs are evaluated by comparing histograms of ‘mock’ ATLAS data (simulated with 30 fb^{-1} and SM TGC parameters) to reference histograms, evaluated as a function of the anomalous TGC parameters, using a binned maximum likelihood fit to one or two dimensional distributions. As an example of the maximum likelihood fit, the transverse momentum distribution of the photon in $W\gamma$ production is shown in Fig. 1, after applying the kinematic cuts. The points with error bars represent “mock” data for one ATLAS experiment. The “mock” data histogram is constructed by sampling each bin according to a Poisson distribution with the mean given by the relevant bin content of the SM reference histogram. The lines in Fig. 1 (bottom) are the reference distributions (i.e. theoretical expectation) for several choices of the anomalous TGC parameters. The contribution of backgrounds to the reference distributions is shown as a shaded histogram. The one and two parameter negative log likelihood curves are shown as a function of the λ_γ and $\Delta\kappa_\gamma$ parameters with the 68, 90, and 95% confidence limits indicated. These confidence limits correspond to the single experiment which has been simulated for this figure. When another ATLAS experiment is simulated, the confidence limits will be different, on account of statistical fluctuations. In order to obtain the best estimate of the limits that will be achieved, it is necessary to average the confidence limits over many simulated ATLAS experiments (we use 5000 simulated experiments here).

When extracting the confidence intervals, the systematic uncertainties are estimated by replacing the histograms which represent the ‘mock’ ATLAS data with histograms which use a different model assumption. The reference histogram assumptions are not changed. The change in the model assumptions causes a shift in the preferred value for each anomalous TGC parameter. This shift is independent of luminosity and is taken as a pessimistic estimate of the systematic error, since it is likely that it will be possible to extract corrections for many of these systematic effects directly from the data. The following systematic effects have been studied: (1) Background rate systematics are evaluated by varying the background process k -factor in the ‘mock’ data histograms

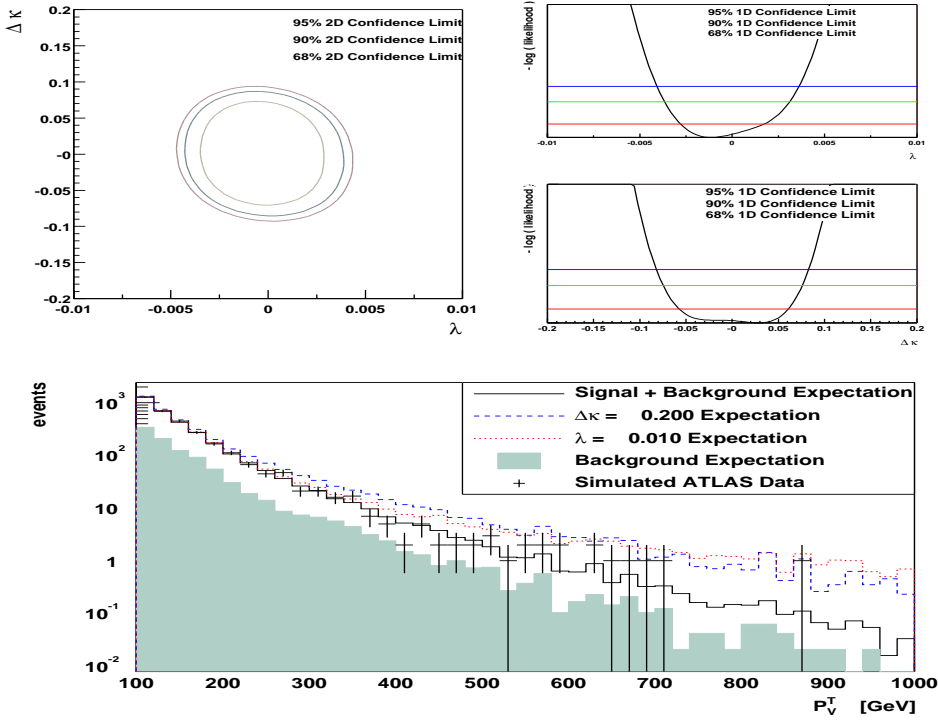


FIGURE 1. The transverse momentum distribution of the photon in $W\gamma$ production is shown (bottom), together with the confidence intervals (top) which may be extracted from this distribution.

from 1.5 up to 2 and down to 1. (2) Parton density function systematics are evaluated by replacing the CTEQ4 [25] PDF's which have been used for the all simulations with the CTEQ3 [26] series PDF's in the 'mock' data histograms. (3) Systematics arising from neglected higher orders are evaluated by varying the renormalisation and factorisation scales up and down by a factor 2 for the WZ signal simulation. (4) Detector related systematics are evaluated by simply turning off the detector smearing in the event generation software chain, which represents the shift in the results that would arise if the ATLAS detector were to be replaced by a fictional 'perfect' detector. Since the overall normalisation of the distributions does not enter into the maximum likelihood fit, uncertainties related to luminosity do not enter. These systematic effects are uncorrelated and are added in quadrature to obtain the total systematic error for the measurements.

The transverse momentum of the photon or Z -boson (P_V^T) has been the traditional means of extracting limits on the anomalous TGC's at hadron colliders because it can be reconstructed without the assumptions necessary for reconstructing the neutrino four-momentum and it projects out the central, high diboson mass production regime where the anomalous TGC's are enhanced.

In addition to simple one dimensional distributions like the one shown in Fig. 1, we have studied two-dimensional distributions and have derived and applied a variation of the optimal observables technique for hadron colliders (see [6]). In order to produce reference histograms for two dimensional distributions in a reasonable amount of computer time, the number of bins in each dimension is reduced, which can reduce the sensitivity

to these distributions.

For the λ_Z , λ_γ , and $\Delta\kappa_\gamma$ parameters, a maximum likelihood fit to the one dimensional P_V^T distribution gives the most stringent 95% confidence intervals,

$$\begin{array}{rclcl} -0.0065_{\text{stat.}}, & -0.0032_{\text{syst.}} & < \lambda_Z < & +0.0066_{\text{stat.}}, & +0.0031_{\text{syst.}} \\ -0.0033_{\text{stat.}}, & -0.0012_{\text{syst.}} & < \lambda_\gamma < & +0.0033_{\text{stat.}}, & +0.0012_{\text{syst.}} \\ -0.073_{\text{stat.}}, & -0.015_{\text{syst.}} & < \Delta\kappa_\gamma < & +0.076_{\text{stat.}}, & +0.0076_{\text{syst.}} \end{array} \quad (1)$$

The dominant systematic effects are theoretical, with the parton density functions providing the biggest contribution to the λ_Z limit, the modelling of QCD corrections being the biggest contribution to the λ_γ limit, and the background rate being the biggest contribution to the $\Delta\kappa_\gamma$ distribution.

The best 95% confidence intervals for the $\Delta\kappa_Z$ and Δg_Z^1 parameters are obtained using the two dimensional P_Z^T vs. P_{lw}^T distributions,

$$\begin{array}{rclcl} -0.10_{\text{stat.}}, & -0.024_{\text{syst.}} & < \Delta\kappa_Z < & +0.12_{\text{stat.}}, & +0.024_{\text{syst.}} \\ -0.0064_{\text{stat.}}, & -0.0058_{\text{syst.}} & < \Delta g_Z^1 < & +0.010_{\text{stat.}}, & +0.0058_{\text{syst.}} \end{array} \quad (2)$$

The dominant systematic effect for these parameters comes from our theoretical understanding of the proton structure (PDF's).

Since each anomalous TGC appears differently in the matrix elements, they exhibit different sensitivity to each distribution. The λ -type couplings, for example, appear proportional to energy squared and $\sin\theta_V^*$, which makes them very sensitive to the P_V^T distribution. The κ -type couplings and Δg_Z^1 are sensitive to the vector-boson helicity, and so the transverse momentum of the charged lepton from the W^\pm (which acts like a projection operator) is also a sensitive distribution.

For most of the anomalous TGC parameters, the confidence intervals are dominated by statistics. This remains true for low luminosity integrated luminosities in excess of 100 fb^{-1} . This is because the sensitivity is dominated by the few events out in the high transverse momentum tails, where the size of the event samples will always be limited regardless of the total diboson event rate. The Δg_Z^1 parameter sensitivity behaves very differently from the other parameters, since this anomalous coupling parameter is more sensitive to systematic effects, and a careful understanding and evaluation of the systematic uncertainties will be particularly important for measurements of this parameter at the LHC. In addition to PDF's, detector related systematic effects will be of importance for measurements of this parameter, particularly if two dimensional distributions are employed.

An improvement in the statistical confidence intervals can be realized for certain TGC parameters (e.g. $\Delta\kappa_Z$) by using the Optimal Observable distributions (OO) derived in Ref. [6]. However, the calculation of the OO's requires more in the way of reconstruction and phenomenological input², and so these distributions are much more sensitive to systematic effects. The systematic errors dominate the confidence intervals for the OO's,

² To calculate the OO for a particular event, the centre-of-mass system needs to be fully reconstructed such that all particle momenta are known, and phenomenological parton density functions are included in the calculation.

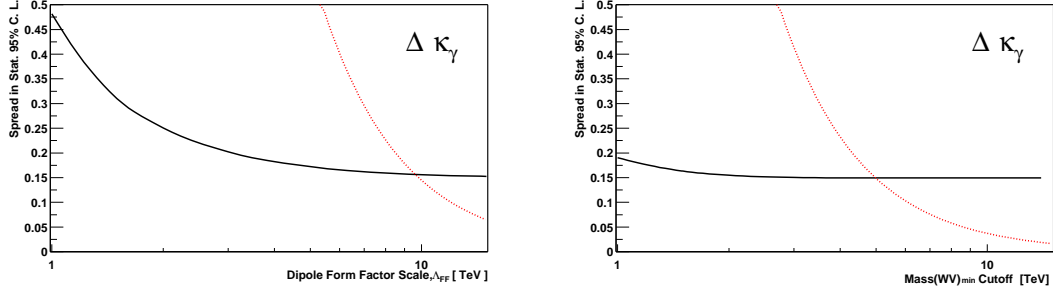


FIGURE 2. The spread in statistical 95% confidence intervals (solid lines) are shown as a function of the dipole form factor scale assumption Λ_{FF} (left) and as a function the diboson mass cutoff (right) for the $\Delta\kappa_\gamma$ parameter in $W\gamma$ production at the LHC. The dotted lines indicate the approximate Born level unitarity limits.

and no improvement in sensitivity is realized. If the systematics can be controlled to a degree beyond what has been assumed in this work, OO's may provide a viable means of measuring the anomalous TGC's.

For the results presented thus far, the anomalous TGC's have been assumed constant, which would be in violation of unitarity at high energy scales. The most common approach for safe-guarding unitarity is to multiply the anomalous couplings by a form factor $(1 + \frac{M_{WV}^2}{\Lambda_{\text{FF}}^2})^{-n}$ (with $n = 2$) which goes smoothly to zero at high energy scales. The form factor scale is usually chosen to be so large for Tevatron analyses ($\Lambda_{\text{FF}}=2$ TeV) that the effects of the form factor are not apparent at the scale at which the experiment probes. As an example, the spread in the $\Delta\kappa_\gamma$ confidence intervals are shown as a function of Λ_{FF} in Fig. 2 (left). The limits improve with increasing Λ_{FF} until an asymptotic limit is reached at about 3-5 TeV, meaning the limits presented above would not be degraded for $\Lambda_{\text{FF}} \geq 5$ TeV.

We advocate against an approach which uses a form factor scale which is significantly smaller than the asymptotic Λ_{FF} value (5 to 10 TeV at the LHC, and about 2 TeV at the Tevatron). The primary argument in support of this philosophy is that the Λ_{FF} defines the scale at which the effective Lagrangian description (wherein the new physics has been integrated out and described in terms of a small number of low-dimensional operators) breaks down. Effectively, a scale has been reached at which the effects of the new physics are directly visible. There is no reason to expect the effects of this new physics to turn off at that scale—rather it will appear directly, but will not be parameterisable in terms of the effective TGC Lagrangian. If a form factor scale smaller than the asymptotic value is used, then it will be absolutely essential to *neglect data* collected at the scales where the assumed form factor operates. This is because in that energy regime, the effective model Lagrangian is fully constrained to the Standard Model (since the anomalous TGC's $\rightarrow 0$ at Λ_{FF}), and it makes no sense to include such data in a fit to extract the anomalous TGC's. However, the data which is collected at the largest scales is potentially the most interesting, and one does not wish to be in a position where it needs to be discarded.

We prefer to avoid the unnecessary dependence of experimental limits on the two extra parameters (n and Λ_{FF}) in the form factor choice by reporting experimental anomalous TGC confidence limits as a function of the diboson invariant mass being probed. This is demonstrated in Fig. 2 (right), wherein the spread in the λ_γ confidence intervals are shown as a function of a diboson invariant mass cutoff (the minimum of the two reconstructed mass solutions is used) which is applied to the data. For example, the limits at $\text{Mass}(WV)_{\text{min}} = 2$ TeV use only the data for which the reconstructed minimum mass solution is less than 2 TeV. An asymptotic limit is reached at about 3 TeV, meaning the LHC is sensitive to diboson masses up to about 3 TeV. This treatment ensures unitarity, without the need to introduce new parameters to parametrise the form factor behaviour. The unitarity limit is superimposed on the plots as a dotted line in Fig. 2. The region above the solid line is excluded by the experiment, while the region to the right of the dotted line is excluded by unitarity. Reporting the anomalous TGC limits as a function of the diboson mass makes the ultimate mass reach of the experiment immediately evident, while allowing the interpretation of results at any mass scale. Further, if an anomalous coupling ‘turns on’ or ‘turns off’ at some mass scale, that would be reflected in the limits.

In the scenario where anomalous TGC measurements at LHC are inconsistent with the Standard Model, it would be preferable to measure the energy dependence of the anomalous TGC parameters directly, rather than assuming some energy dependence in the model. A large data sample of diboson events will be necessary to perform such a measurement, because the data needs to be separated out into bins of diboson mass. For Fig. 3, ‘mock’ ATLAS data has been generated with bare coupling $\lambda_{\gamma 0} = 0.04$ and a dipole ($n=2$) form factor with $\Lambda_{\text{FF}} = 1500$ GeV. This ‘mock data’ is then compared to reference histograms of the bare coupling $\lambda_{\gamma 0}$ (i.e. the reference histograms do not use a form factor) for each of the diboson mass bins. The events have been separated out into diboson mass bins ranging from 250 GeV to 3000 GeV with variable width, to ensure adequate statistics in each bin. The behaviour of the couplings as a function of energy is clearly visible. A fit to the dipole form factor function is also indicated with a solid line. The parameters which were used to generate the ‘mock’ data are reproduced within the precision of the fit.

RADIATION ZERO IN $W\gamma$ PRODUCTION

The radiation zero refers to a particular center-of-mass frame emission angle of the photon with respect to the anti-quark ($\cos \theta_{\bar{q}, \gamma^*}$) in $W\gamma$ production which is forbidden by subtle gauge cancellations (an approximate radiation zero exists for WZ production). The radiation zero has yet to be observed experimentally.

For hadronic collisions, the pseudorapidity difference between the photon and charged lepton $\eta_\gamma - \eta_{l^\pm}$ is normally used to demonstrate the effects of the radiation zero. For $p\bar{p}$ collisions, this distribution shows the characteristic antisymmetric shape which many people have claimed gives $p\bar{p}$ experiments an advantage over pp experiments. For symmetric proton-proton collisions, it is not possible to ascertain from which beam the quark or antiquark arises, and this washes out the radiation zero, such that it shows

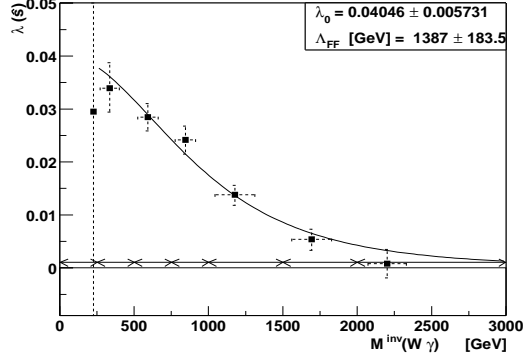


FIGURE 3. Measurement of the λ_γ parameter as a function of energy is demonstrated using 30 fb^{-1} integrated luminosity for $W\gamma$ production. The ‘mock’ ATLAS data has been generated with $\lambda_{\gamma 0}=0.04$ using a dipole form factor of scale $\Lambda_{\text{FF}} = 1500 \text{ GeV}$. The solid line is a fit to Λ_{FF} and the bare coupling λ_{Z0} assuming the dipole form factor. The arrows along the x -axis indicate the diboson mass bin widths.

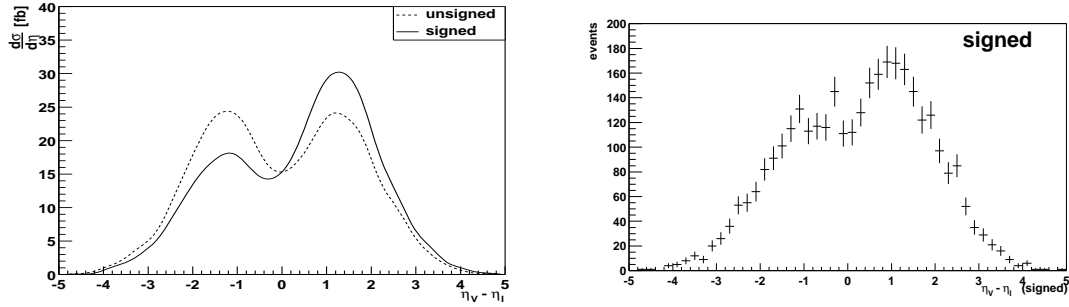


FIGURE 4. The rapidity separation of the γ from the l_W^\pm is shown for $W\gamma$ production at the LHC. For the solid lines in the theoretical distribution on the left, the rapidity separation has been ‘signed’ according to the overall boost of the event. The distribution for 30 fb^{-1} of LHC data is shown right.

up only as a small dip at $\eta = 0$. The idea of “signing” the quark direction according to the overall boost of each event was introduced in Ref. [27, 28] in the context of measuring the electroweak mixing angle with dilepton events. We apply that idea to diboson production in Fig. 4 (left), and find that the characteristic asymmetric radiation zero shape is recovered.

The effect will be clearly observable with 30 fb^{-1} of data from the LHC as shown in Fig. 4 (right), wherein the signed η distribution is plotted for SM $W\gamma$ production.

CONCLUSIONS

The prospects for measuring the $WW\gamma$ and WWZ TGC vertex at the LHC have been assessed in the context of the ATLAS experiment. The leptonic decay channels of $W\gamma$ and WZ diboson production provide clean signatures with signal to background ratios of 1.6 and 17 respectively. For the majority of the anomalous TGC parameters, the

confidence intervals will be dominated by statistics for integrated luminosities up to and beyond 100 fb^{-1} . For the Δg_Z^1 parameter, our ability to model the proton structure with the parton density functions will be a challenging systematic.

Dipole form factors have been the conventional means of guaranteeing unitarity in the TGC Lagrangian. The parametrisation of the form factors is arbitrary, and introduces unnecessary dependence on the parametrisation choice into the experimental results. We have argued that it is preferable to report the limits as a function of a diboson invariant mass cutoff which is applied to the data. The LHC will directly probe diboson invariant masses up to about 3 TeV. In this mass regime, the limits reported in this paper are unitarity safe and are presented without any cutoff of form factor. In the scenario where non-standard anomalous TGC parameters are observed, the LHC event rate will be sufficiently large to bin the data according to the diboson invariant mass, and measure the energy dependence of the couplings directly.

The expected LHC confidence limits for 30 fb^{-1} (including systematic effects) are $-0.0073 < \lambda_Z < 0.0073$, $-0.11 < \Delta \kappa_Z < 0.12$, $-0.0086 < \Delta g_Z^1 < 0.011$, $-0.0035 < \lambda_\gamma < 0.0035$, and $-0.075 < \Delta \kappa_\gamma < 0.076$.

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REFERENCES

1. ATLAS Detector and Physics Performance Technical Design Report, Tech. rep., CERN/LHCC/99-15 (1999).
2. Marques, C., Maio, A., Pallin, D., and Dobbs, M., “W mass measurement with Atlas,” in *Physics at LHC 13-17 July 2004, Vienna, Austria*, 2005.
3. Sliwa, K., Riley, S., and Baur, U., Effects of possible extensions to rapidity coverage of the ATLAS detector on the determination of $\sin^2 \theta_{eff}(M_Z^2)$, Tech. rep., CERN-ATL-PHYS-2000-018 (2000).
4. Bell, P., *Anomalous quartic couplings at OPAL and the system test of the ATLAS barrel SCT*, Ph.D. thesis, Birmingham University, Birmingham, U.K. (2003).
5. Dobbs, M., Frixione, S., Laenen, E., and Tollefson, K., editors, *Les Houches guidebook to Monte Carlo generators for hadron collider physics*, 2004, hep-ph/0403045.
6. Dobbs, M., and Lefebvre, M., Prospects for Probing the Three Gauge-boson Couplings in $W + Z$ Production at the LHC, Tech. rep., CERN-ATL-PHYS-2002-023 (2002).
7. Dobbs, M., and Lefebvre, M., Prospects for Probing the Three Gauge-boson Couplings in $W + \text{Photon}$ Production at the LHC, Tech. rep., CERN-ATL-PHYS-2002-019 (2002).
8. Dobbs, M., *Probing the Three Gauge-boson Couplings in 14-TeV Proton Proton Collisions*, Ph.D. thesis, University of Victoria, Victoria, Canada (2002), uMI-NQ-68128.
9. Mackay, C., *The Electromagnetic Calorimeter For CMS and a Study of the $W W \gamma$ Vertex*, Ph.D. thesis, Brunel University (1998).

10. Müller, T., Neuberger, D., and Thümmel, W., Sensitivities for anomalous WWgamma and ZZgamma couplings at CMS, Tech. rep., CERN-CMS-NOTE-2000-017 (2000).
11. Mackay, C., Observing anomalous di-boson couplings in the WWgamma vertex at CMS, Tech. rep., CERN-CMS-NOTE-2001-052 (2001).
12. Mackay, C., and Hobson, P., Sensitivity of CMS to CP conserving anomalous di-boson couplings in Wgamma events, Tech. rep., CERN-CMS-NOTE-2001-056 (2001).
13. Barate, R., et al., *Phys. Lett.*, **B453**, 107–120 (1999).
14. Abreu, P., et al., *Phys. Lett.*, **B456**, 310–321 (1999).
15. Acciarri, M., et al., *Phys. Lett.*, **B436**, 437–452 (1998).
16. Abbiendi, G., et al., *Eur. Phys. J.*, **C8**, 191–215 (1999).
17. Mackay, C., and Hobson, P., Observing Anomalous Di-boson couplings in Z gamma gamma and Z Z gamma vertices at CMS, Tech. rep., CERN-CMS-NOTE-2002-028 (2002).
18. Hassani, S., Prospects for Measuring Neutral Gauge Boson Couplings in ZZ Production with the ATLAS Detector, Tech. rep., CERN-ATL-PHYS-2002-023 (2002).
19. Hassani, S., Prospects for Measuring Neutral Gauge Boson Couplings in Zγ Production with the ATLAS Detector, Tech. rep., CERN-ATL-PHYS-2002-012 (2002).
20. Richter-Was, E., Froidevaux, D., and Poggioli, L., ATLFAST 2.0 a fast simulation package for ATLAS, Tech. rep., CERN-ATL-PHYS-98-131 (1998).
21. Baur, U., Han, T., and Ohnemus, J., *Phys. Rev.*, **D48**, 5140–5161 (1993).
22. Baur, U., Han, T., and Ohnemus, J., *Phys. Rev.*, **D51**, 3381–3407 (1995).
23. Sjostrand, T., et al., *Comput. Phys. Commun.*, **135**, 238–259 (2001).
24. Kelly, M., *Test of the standard model of electroweak interactions by measuring the anomalous WWγ coupling at $\sqrt{s} = 1.8 \text{ TeV}$* , Ph.D. thesis, Notre Dame, South Bend Indiana (1996).
25. Lai, H. L., et al., *Phys. Rev.*, **D55**, 1280–1296 (1997).
26. Lai, H. L., et al., *Phys. Rev.*, **D51**, 4763–4782 (1995).
27. Fisher, P., Becker, U., and Kirkby, J., *Phys. Lett.*, **B356**, 404–408 (1995).
28. Baur, U., Keller, S., and Sakumoto, W. K., *Phys. Rev.*, **D57**, 199–215 (1998).